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14. ABSTRACT
Along the South American coast, there have been several earthquakes of great magnitude—between 7.5 and 9.5 Mw, with ruptures 50 km to 950 km long, producing maximum intensities between VII and X (MM)—particularly in two seismic gaps located in southern Peru and northern Chile. In these places, two large earthquakes occurred in the 19th century, in 1868 and in 1877, establishing the possibility of the seismic gap hypothesis: *earthquake hazard increases with the time since the last large earthquake of long rupture length occurred, forming a seismic gap at whose ends will occur seismic activity of small magnitude and minor rupture length* (Kelleher, 1972). In 1995, 2001, and 2007, earthquakes occurred within the limits of both gaps. They were felt and had light effects in cities in western Bolivia, especially in La Paz. Of major magnitude, they occurred within the limits of gaps located in the coupling zone of the Nazca and the South American plates.

The above-mentioned earthquakes were here used to generate the characteristics of the 19th-century earthquakes. The effects of such an earthquake today would be catastrophic for the city of La Paz, situated in a basin with rugged topography, abrupt slopes, a geology of slightly compacted and highly eroded soils, and a complex hydrology of surface and underground rivers. Completing the picture are expanding, disorganized demographics. The city could be highly vulnerable to an earthquake with characteristics of the 19th-century events. The EGF method (Empirical Green Function, Irikura, 1986) was applied to an earthquake in Peru on 15/08/2007 and an aftershock on 16/08/2007, registered at the LPAZ station. Numerical analyses of the synthetic and principal seismograms (short period) show a correlation for frequencies lower than 10 Hz and predominance between 0.05 and 2.5 Hz.

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SYNTHETIC SEISMOGRAM STUDY OF THE EASTERN CENTRAL ANDES

Estela Minaya, Evanz Lázaro, Percy Aliaga, Magaly Gonzalez, and Wilfredo Cano

Observatorio San Calixto

Sponsored by the Air Force Research Laboratory

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ABSTRACT

Along the South American coast, there have been several earthquakes of great magnitude—between 7.5 and 9.5 Mw, with ruptures 50 km to 950 km long, producing maximum intensities between VII and X (MM)—particularly in two seismic gaps located in southern Peru and northern Chile. In these places, two large earthquakes occurred in the 19th century, in 1868 and in 1877, establishing the possibility of the seismic gap hypothesis: *earthquake hazard increases with the time since the last large earthquake of long rupture length occurred, forming a seismic gap at whose ends will occur seismic activity of small magnitude and minor rupture length* (Kelleher, 1972). In 1995, 2001, and 2007, earthquakes occurred within the limits of both gaps. They were felt and had light effects in cities in western Bolivia, especially in La Paz. Of major magnitude, they occurred within the limits of gaps located in the coupling zone of the Nazca and the South American plates.

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The EGF method (Empirical Green Function, Irikura, 1986) was applied to an earthquake in Peru on 15/08/2007 and an aftershock on 16/08/2007, registered at the LPAZ station. Numerical analyses of the synthetic and principal seismograms (short period) show a correlation for frequencies lower than 10 Hz and predominance between 0.05 and 2.5 Hz.

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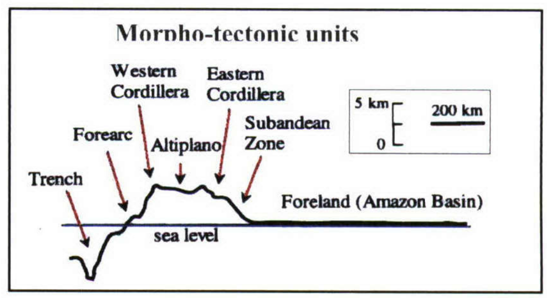
OBJECTIVES

To estimate, from synthetic seismograms, the effects in the Central Andes of earthquakes that have taken place at intermediate depths on the coast of Peru and Chile, and specifically to estimate local intensities in the most vulnerable areas. To verify through this research estimates of attenuation. To increase understanding, and capacities for regional monitoring, of earthquakes in the Central Andes and surrounding areas.

RESEARCH PERFORMED

The area of study is located in the Eastern Central Andes, in the region where the Nazca Plate subducts at 30° dip the South American Plate (along the trench). The area is characterized by Morpho-tectonic variations transversal to the coastline summarized by the following Morpho-tectonic units: Forearc, Western Cordillera, Altiplano, Eastern Cordillera, Sub Andean, and Foreland (Lamb et al., 1997; Gregory-Wodzicki, 2000). See Figure 1.



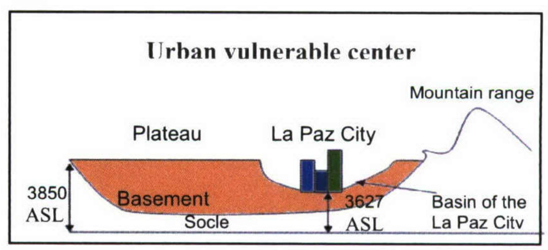


Figure 1. Historical earthquakes along the coast of South America from 4° to 40° and areas of rupture and seismic gaps related to the study area.

The seismic history of the South American coast between 4° and 40° south reveals the relative frequency of occurrence for earthquakes of magnitudes 7.5 to 9.5 Mw, lengths of rupture between 50 km and 950 km, and maximum intensities near epicenter of VII to X (MM). In some zones, moreover, it is possible to apply the seismic gap hypothesis: *the hazard of an earthquake increases with the time since the last large earthquake produced a very long rupture within which seismic activity of small magnitude and short rupture length will occur at the ends* (Kelleher, 1972). It is possible to apply this hypothesis to two earthquakes that occurred in the 19th century, in 1868 and in 1877, the main earthquakes in this study (Figure 2).

Earthquakes occurred on 30/07/1995 and 23/06/2001 at the ends of the gaps of the earthquakes previously mentioned that reinforce the probability of the hypothesis that great earthquakes could occur in each seismic gap with characteristics similar to the 19th century earthquakes, and whose effects in the urban centers of Bolivia's western region could be catastrophic. This evaluation of the geological conditions of urban centers in the Eastern Central Andes permitted selection of one of the more vulnerable cities, La Paz (Figure 1).

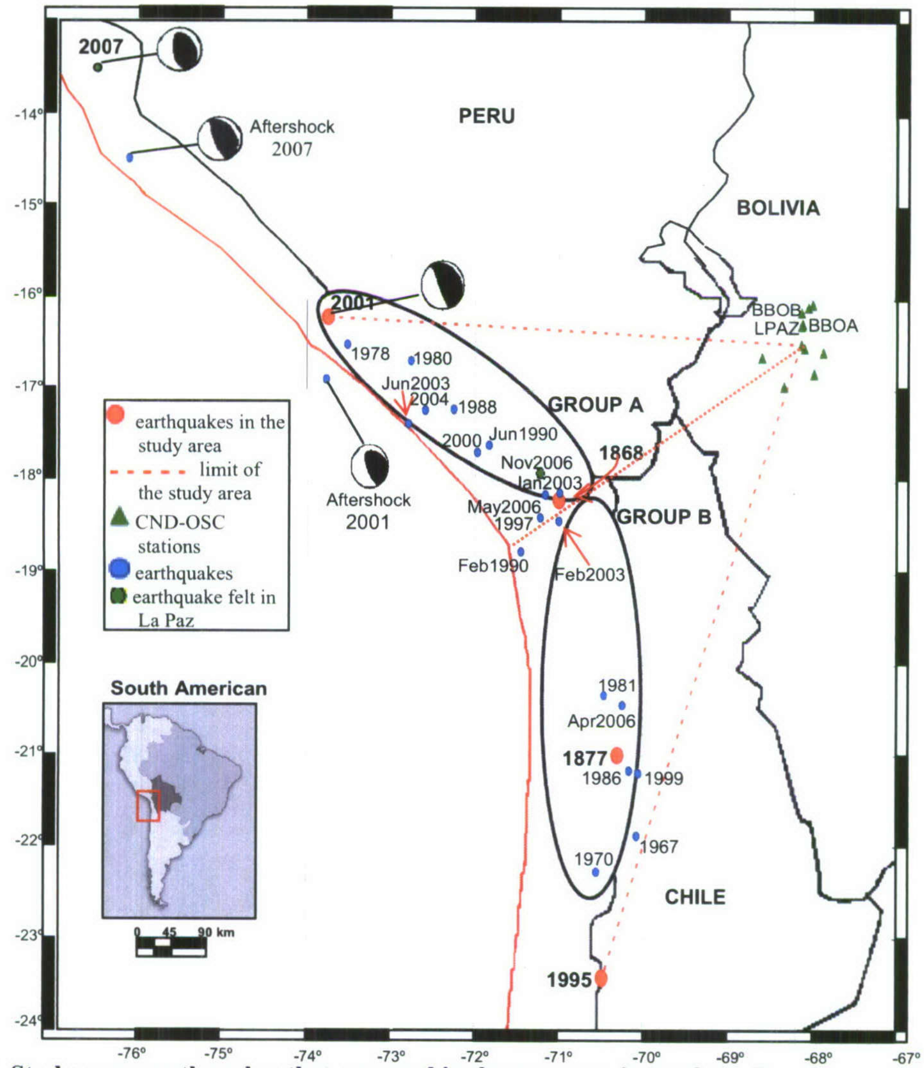


Figure 2. Study area: earthquakes that occurred in the two gaps, in southern Peru (group A) and in northern Chile (group B); earthquakes felt in La Paz. See Table 1.

Geological Conditions of La Paz

The city of La Paz,, situated between the Altiplano and the Western Cordillera, occupies an erosion basin formed by intense glaciation processes. These processes have generated topography that is highly sloped and, in some places, very rugged. See Figure 3.

Soils in La Paz are heterogeneous sediments, poorly consolidated, classified into three types of rocks: a base level formed by Paleozoic (Devonian) and Mesozoic (Cretaceous) rocks; a layer above of lacustrine sediments of the La Paz Formation (1.8–0.01 Ma); and sediments produced by four processes of glaciation that correspond to the Miraflores Formation (Figure 3). The basin is crossed by approximately 200 rivers and tributaries, whose flows have generated the high slopes (Figure 3).

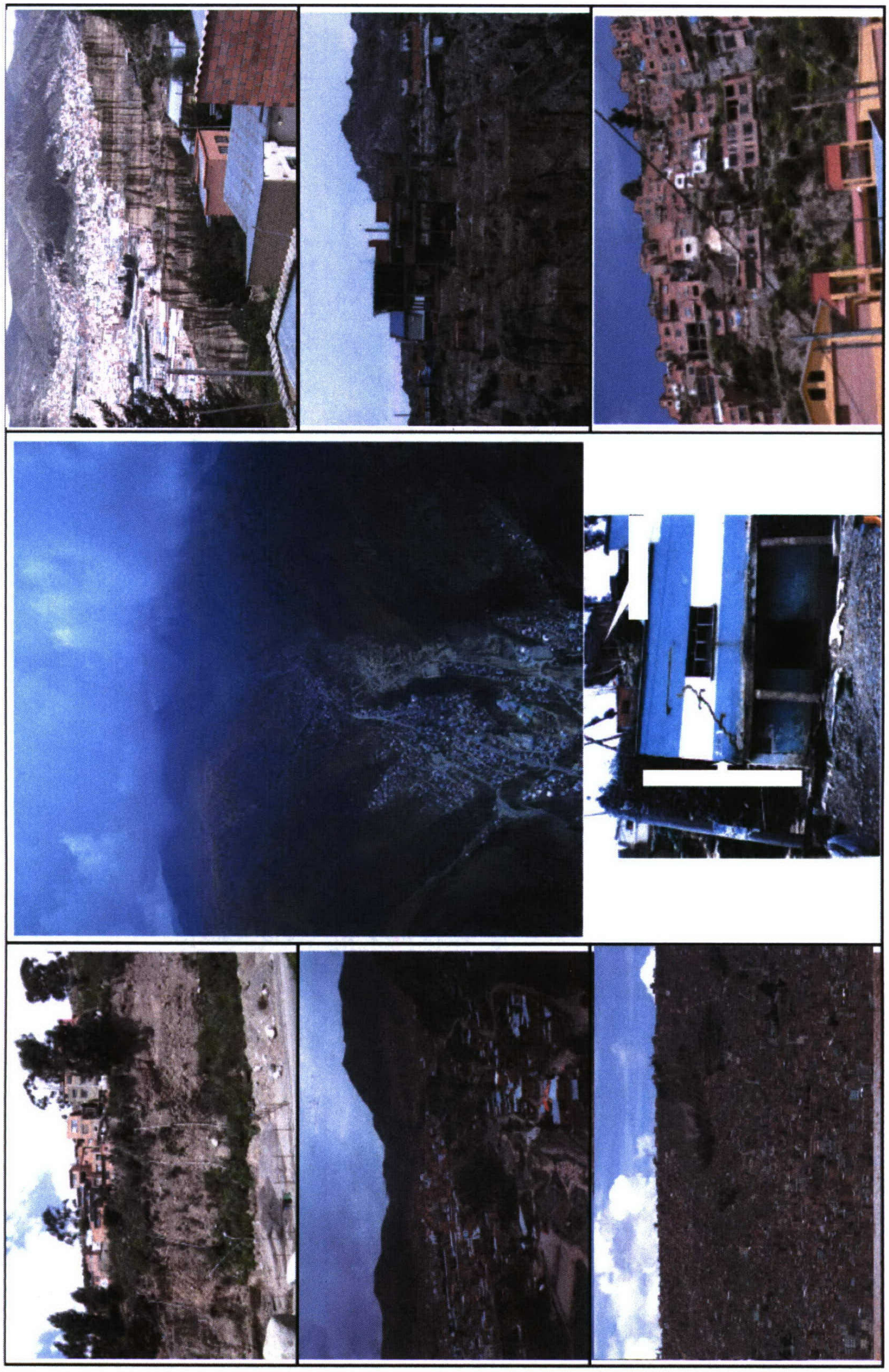


Figure 3. Geological conditions of La Paz.

These geological, hydrogeological, and geomorphological conditions increase the vulnerabilities generated by excessive urban expansion with few controls on construction and human settlements.

Data Selection

Groups A and B in Table 1 and Figure 2 correspond to the earthquakes that occurred in the southern Peru and northern Chile gaps, respectively. Selection corresponded to meeting the following criteria: an interplate earthquake; a seismic event of major magnitude (≥4.5 Mw); and effects felt in La Paz, as occurred during the 2007 earthquakes.

The first part of the evaluation was to characterize the differences and similarities between the earthquakes of groups A and B and the earthquakes of major magnitude of 23/06/2001 and 30/07/1995, using records of the LPAZ and BBOA stations belonging to CND-OSC. The results, shown in Figure 4, correspond to the evolution over time of the frequency content (spectrogram) and FFT (Fast Fourier Transform), specifying the predominant frequencies associated with the source and trajectory of the seismic waves.

To apply Irikura's methodology, we selected the major earthquakes of 23/06/2001 and 15/08/2007 and their aftershocks of 25/06/2001 and 08/08/2007 (Table 1). Records from the BBOB and LPAZ stations were considered for both earthquakes.

Table 1. Earthquakes occurring in the seismic gap and felt in La Paz, with aftershocks.

Group	Date	Time	Latitude [°]	Longitude [°]	Depth [km]	Mw
	13/08/1968	22:00:00.00	-18.00	-70.50	25	9
	15/04/1978	13:49:30.80	-16.50	-73.52	39	5.3
	07/03/1980	8:25:09.30	-16.68	-72.76	53	5.9
	12/04/1988	23:19:55.40	-17.21	-72.25	30	6.9
	08/06/1990	13:49:22.70	-17.60	-71.83	25	5.6
	13/04/1997	23:20:33.90	-18.39	-71.22	37	5.5
	03/08/2000	19:22:08.10	-17.68	-71.97	7	5.8
A	23/06/2001	20:33:14.10	-16.27	-73.64	30	8.4
	25/06/2001*	6:38:47.90	-16.88	-73.77	38	5.7
	03/06/2003	23:58:02.80	-17.37	-72.79	33	5.9
	09/01/2003	7:02:57.70	-18.12	-70.99	32	5.3
	16/09/2004	14:48:52.70	-17.22	-72.59	47	5.4
	25/05/2006	20:48:05.41	-18.14	-71.16	34	5.6
	20/11/2006	14:38:15.00	-17.92	-71.22	35	5.5
	15/08/2007	23:40:57.89	-13.39	-76.60	39	8
	16/08/2007*	11:35:41.79	-14.29	-76.21	35	6
	10/05/1877	-	-21.00	-70.30	40	9
	21/12/1967	2:25:21.00	-21.89	-70.07	20	6.0
	19/06/1970	10:56:13.50	-22.28	-70.55	44	6.1
	21/06/1981	10:30:00.90	-20.34	-70.46	35	5.3
B	20/02/1986	9:16:03.80	-21.17	-70.16	55	5.5
	10/02/1990	3:34:32.00	-18.76	-71.45	37	4.6
	30/07/1995	05:11:23.60	-23.34	-70.29	46	8.0
	17/02/1999	21:58:54.30	-21.20	-70.05	30	5.6
	20/02/2003	20:07:05.10	-18.43	-71.00	29	5.6
	09/04/2006	20:50:46.02	-20.45	-70.24	34	5.8

* Aftershocks

Parameters: ISC until 2004 and NEIC until 2007

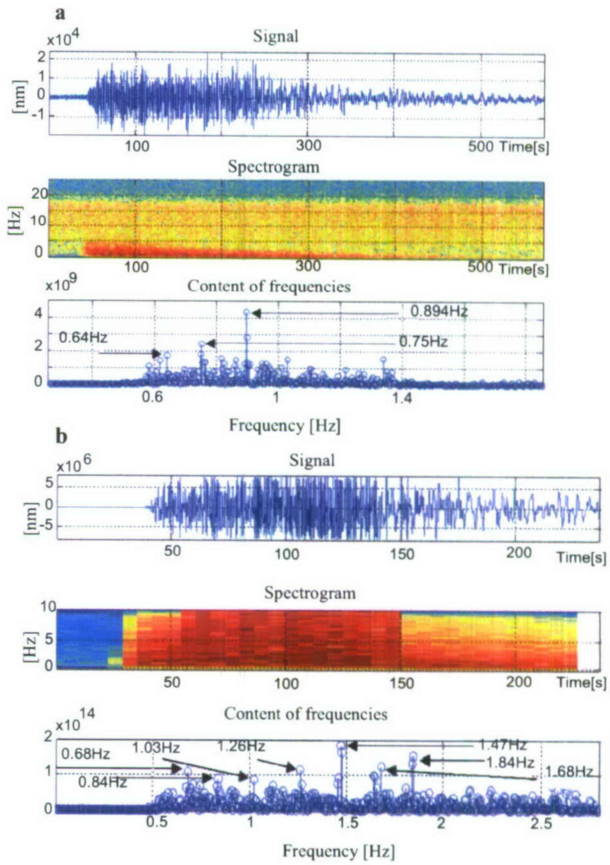


Figure 4. (a) The 07/30/1995 main shock recorded at station BBOA CPZ-D: top, seismogram; middle, spectrogram; bottom, content of frequencies. (b) The 06/23/2001 main shock recorded at the LPAZ station: top, seismogram; middle, spectrogram; bottom, content of frequencies.

Generation of Synthetic Seismogram

The methodology applied in this study was developed by Irikura (1986). The main idea is to use a Green Function on a small earthquake (aftershock or foreshock) to generate a synthetic seismogram corresponding to the main earthquake. This methodology has the advantage over other methods that it does not require numerical treatment of propagation and site effects (Kamae and Irikura, 1998). The aftershock must meet two requirements to be selected: first, it must be near the main earthquake's hypocenter; and second, it must have a focal mechanism similar to that of the main earthquake. The small earthquake is named the **element,** and its record plays the role of the Green Function.

Because earthquakes of the 19th century were not recorded, this methodology is applied to earthquakes with minor characteristics occurring in the gaps, and the results allow us to generate records of these earthquakes.

The earthquake element broken out is a small area called the subfault. An NxN array of subfaults generates an area of the same dimensions as the main earthquake fault, and each subfault generates a synthetic signal. Using the law of scaling and an omega-square model, it is possible to superimpose all these subfault signals to generate synthetic signals for the main earthquake.

The methodology applies the following relations (Irikura, 1986):

$$s(t) = C\sum_{i=1}^{N} \sum_{j=1}^{N}\left(\frac{r}{r_{ij}}\right)F\left(t - t_{ij}\right)* u(t), \quad t_{ij} = \frac{r_{ij} - r_o}{\beta} + \frac{\xi_{ij}}{V_R} \qquad (1)$$

where *u(t)* is the record of the earthquake element, C is a constant obtained from the spectral relation between the main and element earthquakes, r_{ij} is the distance from the subfaults (i,j) to station, r is the distance from the element earthquake to station, t_{ij} is the time delay, r_o is the distance from the start point of the rupture to the station, ξ_{ij} is the distance between the subfaults (i,j) considering one of them as a start point, β is the velocity of the shear wave , and V_R is the rupture velocity. *F(t)* is defined as

$$F(t) = \delta(t) + \frac{1}{n}\sum_{k=1}^{(N-1)n} \delta\left(t - \frac{(k-1)\tau}{(N-1)n}\right), \quad \tau = \frac{16\, S^{1/2}}{7\pi^{3/2}\beta} \qquad (2)$$

where $\delta(t)$ is the Dirac delta function, n is an integer selected to displace the fictitious period $\tau/(N-1)$ to a level out of range of the frequencies of interest, k is the subindex of the summation, N is the number of subfaults (Figure 5), τ is the rise time associated with the stress accumulated before the rupture (Géller, 1976), $\beta = 3.7$ $[km/s]$ is the velocity of the shear wave (theoretical value), and S is the area of the rupture.

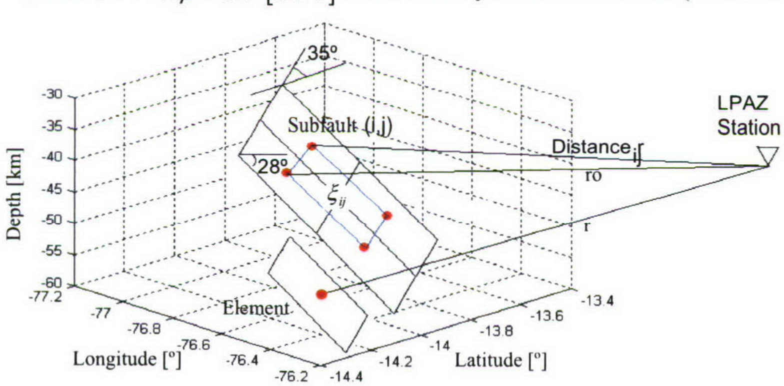


Figure 5. Geometric array of NxN subfaults and fault parameters.

An initial test of this methodology was applied to the main earthquake of 23/06/2001 and its aftershocks of 25/06/2001 using earthquake records at the BBOB station, whose record was saturated for the main earthquake and

did not allow us to generate a synthetic seismogram. The earthquake will be analyzed with records at the LPAZ station in the future. Table 2 presents fault parameters and results.

The second earthquake treated occurred on 15/08/2007, with aftershocks on 16/08/2007. Registered at the LPAZ station, the earthquake was located outside and to the north of the gap in Peru; it was considered because it was felt in La Paz and could allow validation of the Irikura methodology. Fault parameters and results are shown in Table 2 and Figures 6 and 7.

Table 2. Fault parameters and results.

Fault parameters		
Earthquakes:	**23/06/2001**	**15/08/2007**
Strike	310 [°]	325 [°]
Dip	18 [°]	28 [°]
Rupture Length	320 [km]	150 [km]
Velocity S	3.7 [km/s]	3.8 [km/s]
Rupture Velocity	2.96 [km/s]	1.43 [km/s]
Time Rise	25.1 [s]	16 [s]

Results		
Earthquakes:	**23/06/2001**	**15/08/2007**
Subfaults Array	16	4
Corner Frequencies	1.5 Hz, (Main) 3.92 Hz (Element)	156 Hz (Main) 2.97 Hz (Element)
N	4	2
C	235	2.3

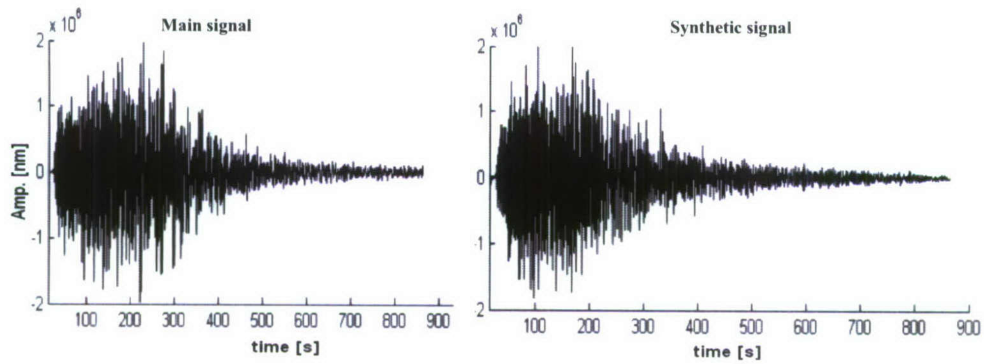


Figure 6. Signal of the main earthquake recorded in SHZ at LPAZ station and the synthetic signal for the earthquake.

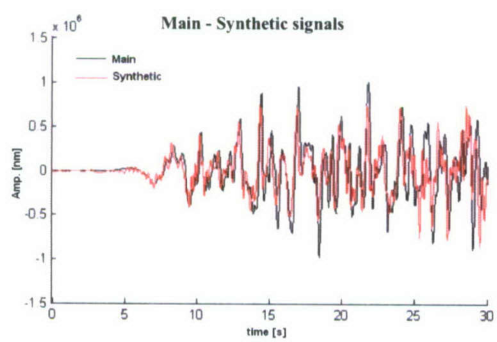


Figure 7. Extended window of 30 [s] to correlate the synthetic and main signals.

CONCLUSIONS

The earthquakes of 30/07/1995 and 23/06/2001 that occurred at the ends of the gaps confirm part of the seismic gap hypothesis.

The La Paz basin has rugged topography and poorly consolidated soils, with uncontrolled human settlement and unregulated construction significantly contributing to increased vulnerability.

Differences in frequency content between the earthquakes of 30/07/1995 and 23/06/2001 are 0.5–1.4 Hz and 0.5–7 Hz. Spectral analysis shows greater frequency dispersion in the earthquake of 23/06/2001 (Peru), which corresponds to a more complex trajectory than the 1995 earthquake (Chile).

To model a synthetic signal with characteristics associated with the 19th-century earthquakes, we tested the method of EGF developed by Irikura (1986), a robust tool that helps solve problems of trajectory and site response, using aftershocks in the Green Function. This methodology was first applied to the earthquake of 23/06/2001, but the results are incomplete.

The second application was to the 15/08/2007 earthquake, recorded over a short period at station LPAZ. Seismograms of the main earthquake and the synthetic seismograms have the same correlations for frequencies less than 10 Hz and frequency predominance between 0.05 and 2.5 Hz.

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